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[54] DEPTH-RESOLVED SPECTROSCOPIC OPTICAL COHERENCE TOMOGRAPHY

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[58] Field of Search 356/345, 346, 356/357, 360

[56] References Cited

U.S. PATENT DOCUMENTS

4,063,549	12/1977	Beretsky et al.	128/2
5,158,090	10/1992	Waldman et al.	128/664
5,200,819	4/1993	Nudelman et al.	358/98
5,353,802	10/1994	Ollmar	128/734
5,459,570	10/1995	Swanson et al.	356/345
5,491,524	2/1996	Hellmuth et al.	351/212
5,493,109	2/1996	Wei et al.	250/201.3
5,501,226	3/1996	Petersen et al.	128/691
5,549,114	8/1996	Petersen et al.	128/691
5,565,986	10/1996	Knüttel	356/346
5,644,642	7/1997	Kirschbaum	382/103

OTHER PUBLICATIONS

Optical Coherence-Domain Reflectometry: A New Optical Evaluation Technique, R.C. Youngquist et al., *Optics Letters*, vol. 12, No. 3, pp. 158–160 (Mar. 1997).

Optical Coherence Tomography, D. Huang et al., *Science*, vol. 254, pp. 1178–1181 (Nov. 22, 1991).

Systems and Transforms with Applications in Optics, A. Papoulis, pp. 254–293, McGraw–Hill Book Company (1968).

Maximum–Likelihood Deconvolution, A Journey into Model–Based Signal Processing, J.M. Mendel, pp. 1–77, Springer–Verlag New York Inc. (1990).

Micron–Resolution Biomedical Imaging with Optical Coherence Tomography, J. Izatt et al., *Optice & Photonics News* (Oct. 1993).

Time–resolved studies of stimulated emission from colloidal dye solutions, M. Siddique et al., *Optics Letters*, vol. 21, No. 7 (Apr. 1, 1996).

Laser action in polymeric gain media containing scattering particles, R.M. Balachandran et al., *Applied Optics*, vol. 35, No. 4 (Feb. 1, 1996).

Laser action in strongly scattering media, N.M. Lawandy et al., *Nature*, vol. 368 (Mar. 31, 1994).

Three Ways to Implement Interferencial Techniques: Application to Measurements of Chromatic Dispersion, Birefringence, and Nonlinear Susceptibilities, P.L. Francois et al., *Journal of Lightware Technology*, vol. 7, No. 3 (Mar. 1989).

(List continued on next page.)

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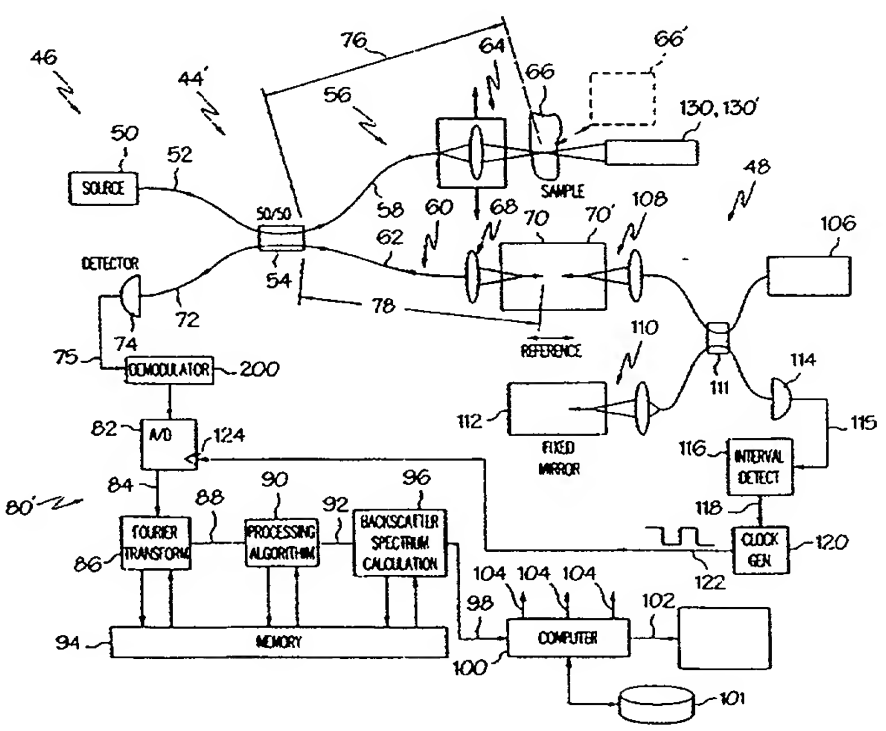
[57] ABSTRACT

A method is described for determining depth-resolved backscatter characteristics of scatterers within a sample, comprising the steps of: acquiring a plurality of sets of cross-correlation interferogram data using an interferometer having a sample arm with the sample in the sample arm, wherein the sample includes a distribution of scatterers therein, and wherein the acquiring step includes the step of altering the distribution of scatterers within the sample with respect to the sample arm for substantially each acquisition; and averaging, in the Fourier domain, the cross-correlation interferogram data, thereby revealing backscattering characteristics of the scatterers within the sample.

15 Claims, 18 Drawing Sheets



OTHER PUBLICATIONS

Precise characterization of the Raman nonlinearity in benzene using nonlinear interferometry, A. Owyoung et al., *Journal of Applied Physics*, vol. 48, No. 2 (Feb. 1977).

Simultaneous Measurement of Dispersion, Spectrum, and Distance with a Fourier Transform Spectrometer, T. Hellmuth et al., *Journal of Biomedical Optics*, vol. 3, No. 1 (Jan. 1998).

Ultrasonic Tissue Characterization of Uveal Melanoma and Prediction of Patient Survival After Enucleation and Brachytherapy, D.J. Coleman et al., *American Journal of Opthalmology*, 112:682–688 (Dec. 1991).

Correlations of Acoustic Tissue Typing of Malignant Melanoma and Histopathologic Features as a Predictor of Death, D. J. Coleman et al., *American Journal of Opthalmology*, 110:380–388 (Oct. 1990).

Theoretical framework for spectrum analysis in ultrasonic tissue characterization, F.L. Lizzi et al., *J. Acoust. Soc. Am.*, 73 (4) (Apr. 1983).

Spectroscopic optical coherence tomography, M.D. Kulkarni et al., Conference on Lasers and Electro–Optics. vol. 9 1996 Technical Digest Series Conference Edition (Jun. 2–7, 1996)

Diagnostic Spectrum Analysis in Ophthalmology: A Physical Perspective, E.J. Feleppa, *Ultrasound in Med. & Biol.*, vol. 12, No. 8 (1986).

Noninvasive Identification of Bladder Cancer with Subsurface Backscattered Light, L.J. Bigio et al., *Progress in Biomedical Optics: Proceedings of Advances in Laser and Light Spectroscopy to Diagnose Cancer and Other Diseases*, Los Angeles, CA (Jan. 23–24, 1994).

Detection of gastrointestinal cancer by elastic scattering and absorption spectroscopies with the Los Alamos Optical Biopsy System, *Progress in Biomedical Optics: Proceedings of Advances in Laser and Light Spectroscopy to Diagnose Cancer and Other Disease II*, San Jose, CA (Feb. 7–8, 1995).

Rapid Near–Infrared Raman Spectroscopy of Human Tissue with a Spectrograph and CCD Detector, J.J. Baraga, *Applied Spectroscopy*, vol. 46, No. 2 (1992).

Theoretical and Experimental Investigations of Elastic Scattering Spectroscopy as a Potential Diagnostic for Tissue Pathologies, J. Boyer et al., *OSA Proceedings on Advances in Optical Imaging and Photon Migration*, vol. 21, Orlando, FL (Mar. 21–23, 1994).